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Requirements for Long-Life Operation of Inert Gas Hollow Cathodes—Preliminary Report

Timothy R. Verhey
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio

and

Gregory S. MacRae
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

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Requirements for Long-Life Operation of Inert Gas Hollow Cathodes-Preliminary Results

by

Timothy R. Verhey
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, OH 44142

and

Gregory S. MacRae
NASA Lewis Research Center
Cleveland, OH 44135

SUMMARY

An experimental investigation was initiated to establish conditioning procedures for reliable hollow cathode operation via the characterization of critical parameters in a representative cathode test facility. From vacuum pumpdown rates, it was found that approximately 1.5 hours were required to achieve pressure levels within 5 percent of the lowest attainable pressure for this facility, depending on the purge conditions. The facility atmosphere was determined by a residual gas analyzer to be composed of primarily air and water vapor. The effects of vacuum pumping and inert gas purging were evaluated. A maximum effective leakage rate of 2.0×10^{-3} sccm was observed and its probable causes were examined. An extended test of a 0.64 cm diameter Mo-Re hollow cathode was successfully completed. This test ran for 504 hours at an emission current of 23.0 amperes and a xenon flow rate of 6.1 sccm. Discharge voltage rose continuously from 15 to 21 volts over the course of the test. The temperature of the cathode body during the test was relatively stable at 1160 °C. Post-test examination revealed ion-bombardment texturing of the orifice plate to be the only detectable sign of wear on the hollow cathode.

I. INTRODUCTION

Hollow cathodes have been used as electron emitters in electron-bombardment ion thrusters for over twenty years, beginning with the development of the plasma bridge neutralizer by Sohl, et al. in 1966[1] for ion beam neutralization. In 1970, Rawlin and Kerslake reported the implementation of a hollow cathode as the electron source for the main discharge in the Space Electric Rocket Test (SERT) II thrusters[2]. Since then, numerous extended tests of hollow cathodes, covering a wide range of conditions, have been performed in this country[2-5] and abroad[6-8]. The success of the SERT II experiment[9] proved the feasibility of the hollow cathodes in mercury ion thrusters in the space environment. Hollow cathode reliability in Hg ion thrusters was also demonstrated in higher power ground-based programs in this country[10,11] and in the Japanese ETS-3 flight test[12].

Inert gases, primarily xenon, have been used exclusively as ion thruster propellants in recent years. The potential for contamination in the propellant-feed systems of inert gases ion thrusters exists and, to date, a systematic investigation of contamination sources and their impact have not been undertaken. The importance of vacuum pumping and the integrity of the evacuated systems are factors that must be addressed.

Concurrent with the change to inert gas propellant, new mission requirements have increased the thruster power levels to 5 to 10 kW and this will likely increase in the future. These demands have extended the hollow cathode operating envelope into untested regions of emission current and temperature. Under the combined impact of these changes, several problems have been uncovered which affect the lifetime of the hollow cathode, and whose solutions require improved understanding of the physical processes internal to the cathode.

Table I summarizes the reported life-testing of hollow cathodes on inert gases and lists the life-limiting phenomena that have been experienced in several instances of device testing. Ramsey[13] and Beattie, et al.[14] have observed cathode orifice erosion over the course of extended tests with xenon propellant. Rawlin observed destructive oxidation of the cathode body tube in the form of cracking and swelling as can be seen in Fig. 1a[15]. The damage was believed to be a consequence of contamination due to atmospheric leaks into the feed system and an improper insert activation procedure. Brophy and Garner found similar cathode body tube swelling and cracking after 500 hours at a 100 A operating point[16]. In recent tests[17], anomalous material formation was found to have occurred within the cathode and at the orifice of the cathode. A photograph of the formation is shown in Fig. 1b. This material is believed to be a barium tungstate resulting from the reaction of the insert material with liberated barium and contaminants in the propellant feed system such as water vapor and oxygen. The above-mentioned phenomena may be facility-related. As a consequence, these issues must be addressed before meaningful long-term life-testing of the hollow cathodes can be undertaken.

Since most of the life-limiting phenomenon observed to date appeared to be related to oxidation, it is possible that system contaminants such as water vapor are responsible. In response to this, the program detailed in this report had two objectives. The first was to examine and quantify contamination levels in a standard hollow cathode test facility in terms of system integrity and oxygen contamination. The second objective was to develop a cathode conditioning and insert activation procedure that minimizes the impact of contamination. Therefore, the focus of this experimental work was to examine the levels of contamination to which an operating hollow cathode is exposed from the propellant feed system and during the activation period of the cathode insert.

II. APPARATUS AND EQUIPMENT

The Cathode and Test Facility

The vacuum facility used in this project is shown schematically in Fig. 2. The hollow cathode device was mounted in a test piece attached to a diffusion-pumped vacuum chamber which had a pumping capacity of 47000 L/s. The test section consisted of two cylindrical stainless steel segments. In order to simulate conditions inside a 30-cm diameter ion thruster, a stainless steel screen with a transparency of approximately 20 percent was inserted between the segments. The chamber upstream of the screen was 30.0 cm deep and 40.0 cm in diameter. A cross-section of the hollow cathode tested here is shown in Fig. 3. The cathode body was a 10.2 cm long, 0.64 cm diameter molybdenum-41-rhenium tube, with a nominal wall thickness of 0.046 cm. A 0.13 cm thick thoriated tungsten plate was electron-beam welded in place at the downstream end of the body tube. A 0.16 cm diameter orifice with a 45° half-angle chamfer on the downstream exit was machined into the plate along the cathode centerline. This hollow cathode geometry was identical to that used in a recent life test of a 30-cm diameter, 5 kW ring-cusp ion thruster[17].

The hollow cathode inserts tested were sintered tungsten cylinders. Each insert had an inner diameter of 0.38 cm, a wall thickness of 0.075 cm, a length of 2.54 cm, and a porosity of 80 percent. The insert was impregnated with a barium-calcium-aluminate oxide compound with a molar ratio of 4:1:1 to provide a dispensing source of barium. A Mo-Re collar was brazed to the upstream end of the insert. Rhenium leads attached to this collar were used to make electrical connections between the insert and the cathode body tube. The insert was placed in the cathode tube in contact with the interior surface of the orifice plate. The leads were spot-welded to the inner surface of the cathode tube to provide the electrical connection and to maintain the insert position.

The cathode tube was mounted to a gas plenum chamber designed to allow access ports for pressure taps for measurement of the internal cathode conditions. The volume of the plenum chamber was 112 cm^3. A stainless steel discharge ignitor electrode was positioned 0.32 cm downstream of the cathode orifice. This electrode was a 6.4 cm long, 1.2 cm wide, and 0.16 cm thick plate mounted on two threaded rods parallel to the cathode axis. A 0.6 cm diameter orifice in the center of the plate was aligned with the cathode orifice so that the discharge plasma would flow through this aperture. A stainless steel anode liner was mounted in the test section with its midpoint 5.1 cm downstream of the cathode. This liner was 15.0 cm long, 19.0 cm in diameter, and was electrically isolated from the cathode.

A coiled swaged heater was friction-fitted on the cathode tube approximately 0.5 cm from the orifice tip as shown in Fig. 3. The heater assembly consisted of a tantalum sheath over a magnesium oxide insulating layer which isolated a tantalum inner conductor. The heater was used to raise the insert into the surface activation temperature region of approximately 1100 °C. At this temperature, the barium in the impregnate migrates to the surface of the insert. The migrating barium lowers the surface work function which lessens the power requirements for discharge maintenance. A conditioning procedure was used to drive contaminants from the surfaces of the insert and cathode, thereby decreasing the probability of destructive surface reaction (oxidation). Surface reactions of this type will be referred to as insert poisoning.

The cathode body temperature was measured during the tests with a type R (Pt-13% Rh/Pt) thermocouple and a 2-color pyrometer (see Fig. 2). The thermocouple was attached to the sidewall of the cathode body tube, in front of the heater, by spot-welding a small piece of tantalum foil to the cathode sidewall, spot-welding the thermocouple to the foil, and then spot-welding another small piece of tantalum foil over the bead of the thermocouple. The final layer of Ta foil provided both a strain relief for the thermocouple leads and a shield to reduce electromagnetic interference.

Extensive work was performed to determine the relative accuracy of the two temperature measurement techniques. While there are several unresolved issues in the measurement techniques, the thermocouple measurements were found to be more accurate during simple thermal heating tests and less susceptible to errors arising from changes in the facility during discharge operation.

<u>The Propellant Feed system</u>

All the propellant feed lines were 0.64 cm diameter 304 stainless steel tubing, except for a 1 meter section of 0.64 cm diameter nylon tubing used to allow a flexible connection to the movable experiment cart. Compression fittings were used throughout the system.

Xenon was used as the propellant. Mass flow rates were monitored using two mass flowmeters that had been calibrated on air. The flowmeter readings were then correlated to a calibration curve obtained by comparing the flow of xenon through these meters with that through another mass flowmeter in series which had recently been calibrated for xenon.

Gas-feed line pressures, upstream of the cathode, were measured with Pirani gauges (calibrated on air). Both a Bayard-Alpert type ionization gauge and a cold cathode gauge were used to monitor pressure levels in the region surrounding the hollow cathode. All of these pressure gauges provided only qualitative data since no special gauge calibration procedures were used. Consequently, the accuracy of the pressure readings is never less than 25 percent[18], which is the typical rated accuracy of the most accurate device used, the ionization gauge. While greater accuracy is possible, the necessary calibration procedures were beyond the scope of this project.

In order to quantify the effects of oxygen contamination in the test facility, it was necessary to measure this constituent in the effluent of the gas-feed system. A residual gas analyzer (RGA) was employed to measure partial pressures of the contaminants. The RGA was mounted at the thruster simulator segment of the test section (see Fig. 2) and sampled system effluent via a differentially-pumped quadrupole mass spectrometer. A dedicated turbomolecular pump maintained the pressure at the RGA sensing head below its operational limit of 10^{-3} Pa. The mass sampling range of the RGA was 1 to 200 amu. Relative gas constituent levels were determined from measured peak heights. The total pressure measurement from the ionization gauge was used to calculate the absolute partial pressures of these constituents.

<u>Cathode power supplies</u>

Three power supplies were required to operate the hollow cathode. A 25 volt, 15 amp current-regulated supply operated the cathode heater. A 1200 volt, low-current ignitor supply provided the high voltage for the discharge breakdown between the cathode and anode. A 60 volt, 120 amps current-regulated power supply provided the necessary current for maintenance of the discharge after ignition. The cathode and all of the simulator surfaces were maintained at facility ground while the anode was isolated from the spool piece.

III. RESULTS AND DISCUSSION

Facility Characterization

The research effort focussed on characterization of contamination levels in the vacuum system. An initial test was conducted to determine the test facility evacuation rate. For this, a pumpdown sequence was initiated starting from atmospheric pressure. A base pressure near 10^{-4} Pa was attained after approximately 1.5 hours of pumping. For the final 1.1 hours of this period, the system was opened to the diffusion-pumped vacuum chamber. The pressure level was reduced by approximately a factor of 2 after an additional 12 hours of pumping, and after 24 hours, an indicated pressure of approximately 9.0×10^{-5} Pa was observed.

The evacuation rate of the test facility when pumping inert gases was also determined. The facility was evacuated as described above and then purged with either argon or xenon gases at a mass flow rate of approximately 32 sccm. The flow was shut off and the intensities of the inert gas peaks were monitored with the RGA. As shown in Fig. 4, both inert gases were rapidly evacuated from the feed system at approximately the same rates. Throughout the testing of the facility, a 0.64 cm diameter vacuum purge line which bypassed the cathode orifice was used to improve the feed-line evacuation rate.

Two techniques were employed to measure the effective rate of leakage into the propellant feed-lines. In one, a specific section of the propellant feed system was evacuated, then isolated. The increase in its internal pressure was monitored via a Pirani gauge and found to nearly linear with time. The average effective leakage rate determined by this fixed volume was approximately 2.0×10^{-3} sccm for the 11.2 m long tubing configuration that was employed in the hollow cathode wear test.

In the second method, the same length of propellant feed-line was evacuated using a helium leak detector. A helium leak check of the system was then performed. This leakage rate, corrected for air, was observed to be significantly below that of the effective leakage rate measured by the first method. The helium leak rate detected provides a value which relates directly to the quantity of helium transferred into the specified feed-line, whereas the fixed volume method provides an effective leakage rate composed of both true leaks in the feed-lines as well as contaminants outgassing from the feed-line surfaces. Since helium is very unlikely to be adsorbed onto the internal surface of the lines[19], the outgassing that occurs will not be detected by the helium leak detector. Consequently, the leak detector should provide a measurement of the true leaks in the feed system only. The remainder of the effective leakage rate should then be due to outgassing from the internal surfaces of the tubing. Using a nominal outgassing rate of 1.6×10^{-2} sccm-m^{-2} for unbaked stainless steel at room temperature[18] and multiplying this by the area of the test configuration results in a total outgassing rate, q, of

$$q = (0.016\,\mathrm{sccm/m^2}) x (0.1644\,\mathrm{m^2}) = 0.0026\,\mathrm{sccm}$$

This is sufficient to account for the quantity of gas evolved in this system that is measured with the fixed volume method. Therefore, the results point towards outgassing as being the primary source of internal feed-system contamination. Procedures, such as feed-line bakeout at high temperatures, have been used to reduce the levels of outgassing in many vacuum systems[18]. However, the impact of these techniques in hollow cathode operation remains to be determined. In addition, alterations to the propellant feed-system such as shortening the length of the lines or changing the types of fittings used may prove to be crucial for alleviating some of the contamination problems that contribute to the effective leakage rate.

A typical RGA scan of the residual gases in the system is shown in Fig. 5. This scan shows that the background atmosphere is composed primarily of N_2, O_2, with peaks at 28 and 32 amu., and water vapor (with peaks at 17 and 18 amu.). Measurements of the background with and without the propellant-feed system opened to the chamber revealed that the propellant feed-lines accounted for approximately 20 percent of the total signal on the RGA, with N_2, O_2, and water vapor being the major components of the line effluent. The presence of oxygen-bearing contaminants in the region of the cathode insert is unacceptable because of the potential for insert poisoning discussed earlier.

A test was performed to determine if repeated inert gas purges could be used to lower contaminant levels within the system. With the vacuum system evacuated to operational levels, a 32 sccm argon flow was established for a 10 minute purge. Following this, the flow was shut off and the lines evacuated. Contamination levels were recorded when the argon specific pressure had dropped to the 10^{-10} torr level on the RGA. The results are shown in Fig. 6 for a sequence of nine such purging cycles. A 30 percent decrease in the H_2O peak and a 35 percent drop in the HO peak were observed. However, the repeated purging had a lesser effect on the N_2 and O_2 levels. Further examination with the RGA would be necessary to distinguish the relative contributions of the different sections of the feed-system.

<u>Wear test of a ring-cusp ion thruster-discharge cathode</u>

A wear test of a hollow cathode was performed to provide additional operational data on this device. This cathode was identical in geometry and construction to that used in a life-test of a 30-cm diameter ring-cusp ion thruster[17]. In order to condition the cathode, the system was first purged for 20 minutes with xenon gas at 27 sccm. Following this, the swaged heater was started at 1.0 amp and raised in 2.0 amp increments at 15 minute intervals to a maximum current of 9.0 amps. At 9.0 A, the cathode body temperature was approximately 1000 °C. The hollow cathode was started by presetting the discharge supply to 60 V and 10 A and increasing the the output voltage of the ignitor power supply until electrical breakdown to the anode occurred.

After ignition, the ignitor supply was shut down and the propellant flow was decreased to 6.1 sccm. For the remainder of the wear test, the emission current was 23.0. The total duration of the test was 504 hours, accumulated in two segments; the first was 195 hours in length and the second was the remaining 309 hours. Two unintended shutdowns occurred, one due to an inadvertently tripped safety interlock and the other due to a building power failure. The cathode remained in the vacuum environment during these shutdowns, and no apparent changes in operating characteristics were noticed after each. Hollow cathode operating characteristics were relatively stable throughout the wear test. The discharge voltage, however, rose continuously from 15.0 to approximately 21.0 volts during the test. No tests have yet been performed to determine the cause of the change in discharge voltage.

Cathode temperature as a function of emission current in shown is Fig. 7. The error bars represent limits of the standard error calculated for the average temperature. This figure also includes curves for the cathode temperature taken for both pre- and post-test conditions, where the I-V curve measurement was repeated. The repeated tests of the I-V characteristic at the pre- and post-test conditions of the cathode shown in Fig. 8 provide evidence of minimal change in hollow cathode operation. The temperature of the cathode body was monitored throughout the test and these measurements are shown in Fig. 9. The temperature reading did not deviate from the average value by more than 6 percent over the course of the wear test. This average cathode tube temperature, approximately 1160 °C, was greater than the recommended operating temperature of 1100 °C[20]. It has been found that the cathode tip temperature is typically approximately 100 °C lower than the maximum insert temperature[4,21]. Thus, it is possible that the insert temperature was near 1300 °C during this test. This high temperature operation would substantially reduce the expected lifetime. Consequently, a method is needed to determine the actual insert operating temperature. Further work must also address the issue of the validity of the thermocouple reading when operated in the complex electromagnetic environment of a discharge plasma.

Over the course of the wear test, the measured orifice diameter did not change within the uncertainty of the measurement. Thus, cathode orifice erosion was negligible at the current levels run in this test. In this test, the criterion established by Rawlin[15]:

$$\frac{J_e}{d_o} \leq 15 A/mm$$

where J_e is the desired emission current and d_o is the cathode orifice size was satisfied. However, the orifice was smaller than that which would be selected using the criterion of 12 Amp/mm as suggested by Kaufman[22]. Additional extended testing of hollow cathodes will be required to validate the correct design criterion.

Fig. 10 shows the orifice plate before and after the test. From the figure, it can be seen that substantial texturing of the orifice plate had occurred. It was also found that, over the course of the test, the ignitor electrode had sagged and begun to intercept the cathode plume on one side. Substantial erosion of the ignitor electrode occurred, leading to deposition of the electrode material over the surfaces of the simulator chamber.

IV. CONCLUDING REMARKS

The results of this preliminary investigation into the facility condition have indicated that several facility effects exist which may influence the life of the hollow cathode. These effects are not test facility-specific and can be used to establish criteria for reliable cathode operation in any facility. The evacuation rates of the propellant-feed system, pumped from atmosphere and from inert gas purge conditions, were determined. The results showed that the pumping system brought the simulator chamber and propellant feed-system to within 5 percent of its base level within 1.5 hours and that the lowest attainable pressure level was achieved within 24 hours of pumping. Thus, pumping the propellant-feed system for a few hours should remove most of the gas contaminants. The inclusion of a vacuum purge line, tapped into the cathode feed-line upstream of the cathode orifice, reduced the impact of the orifice restriction on the system evacuation rate.

The maximum rate of pressure increase in the propellant feed system was determined to be approximately 2 x 10^{-3} sccm of gas flow. This rate is believed to be a combination of physical leakage and outgassing from the system surfaces. Some rough calculations of the outgassing rates for the materials used in this facility along with a leakage rate test performed with a helium leak detector showed that outgassing was an important factor. Further work is required for a thorough understanding of the relative contributions of the different effective leak mechanisms and which techniques can be implemented to alleviate contamination.

One technique that was tested for the decontamination of the propellant-feed system was repeated purging of the feed-lines with an inert gas (argon). This was found to reduce the RGA-measured specific pressures for water, but not oxygen or nitrogen. Further investigation will also be required to quantify the effect of purging on contamination levels. It does, however, appear to be a viable procedure for reducing the pumping time required to attain a specific contamination level.

An extended wear test of a hollow cathode was conducted in the vacuum facility described. The duration of the test was 504 hours, over two segments. The emission current was set at 23.0 amps. The discharge voltage was initially 15 volts but rose continuously to approximately 21 volts by the conclusion of the test. The temperature of the hollow cathode was a relatively constant 1160 °C over the duration of the test. No component failure was experienced by the completion of the test, but texturing of the orifice plate had occurred.

In summary, while a 500 hour test of a hollow cathode was successfully completed, there remain several issues which need to be addressed in order to establish proper operating procedures. These include upgrading the existing propellant feed system to reduce the potential for contamination, instituting procedures such as a feed-line bakeout to reduce interior surface outgassing, investigating the relative contamination in different parts of the vacuum system, particularly in the region of the cathode insert, and making an accurate determination of the insert operating temperature.

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Table I. Summary of Inert Gas Extended Testing of Hollow Cathodes.

Location & Reference	Configuration	Emission Current (amps)	Duration (hours)	Observations
Electro-Optical Systems, 13	2 cathodes, argon	4.0	500/600	insert oxidation, cathode orifice plate erosion.
Hughes Research Labs., 14	2 cathodes for main source, xenon, thruster-based	7.0/2.0	4300	cathode orifice plate erosion
LeRC, 15	3 cathodes for main source, xenon, thruster-based	32.0/2.5	567	cracked and swollen cathode tubes
JPL, 16	cathode, argon	100	1000	cracked and swollen cathode tube
LeRC, 17	xenon, thruster-based	19.0/6.0	890	anomalous material formation
LeRC	cathode, xenon	23.0	504	cathode orifice plate erosion

Thruster-based refers to main and neutralizer pair of hollow cathodes

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

a.

b.

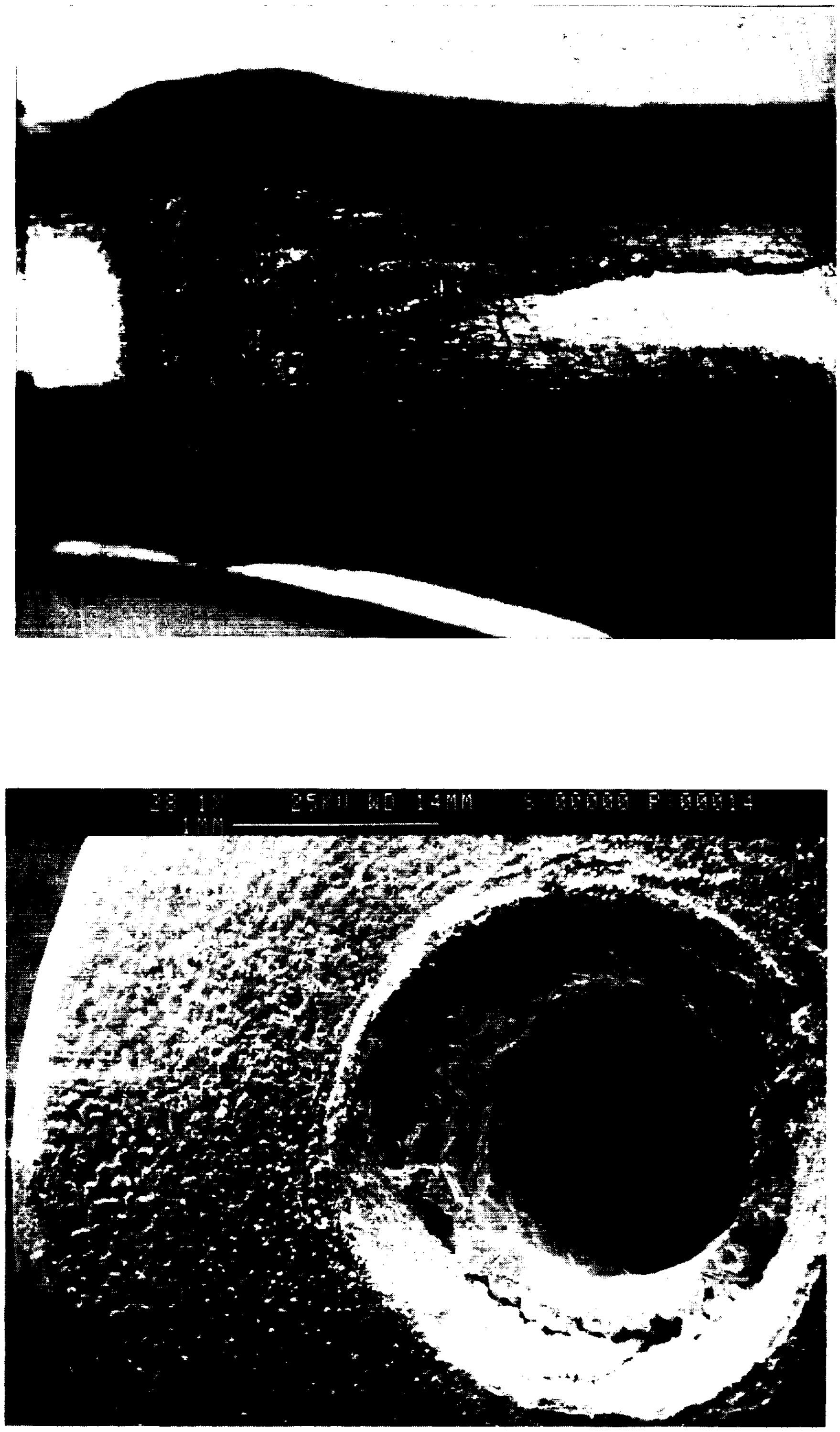


Figure 1. Examples of hollow cathode operational problems. Photo a. shows a tantalum hollow cathode tube that has swelled and cracked due to oxidation. Photo b. displays build up of anomalous material at a cathode orifice which occurred in operation.

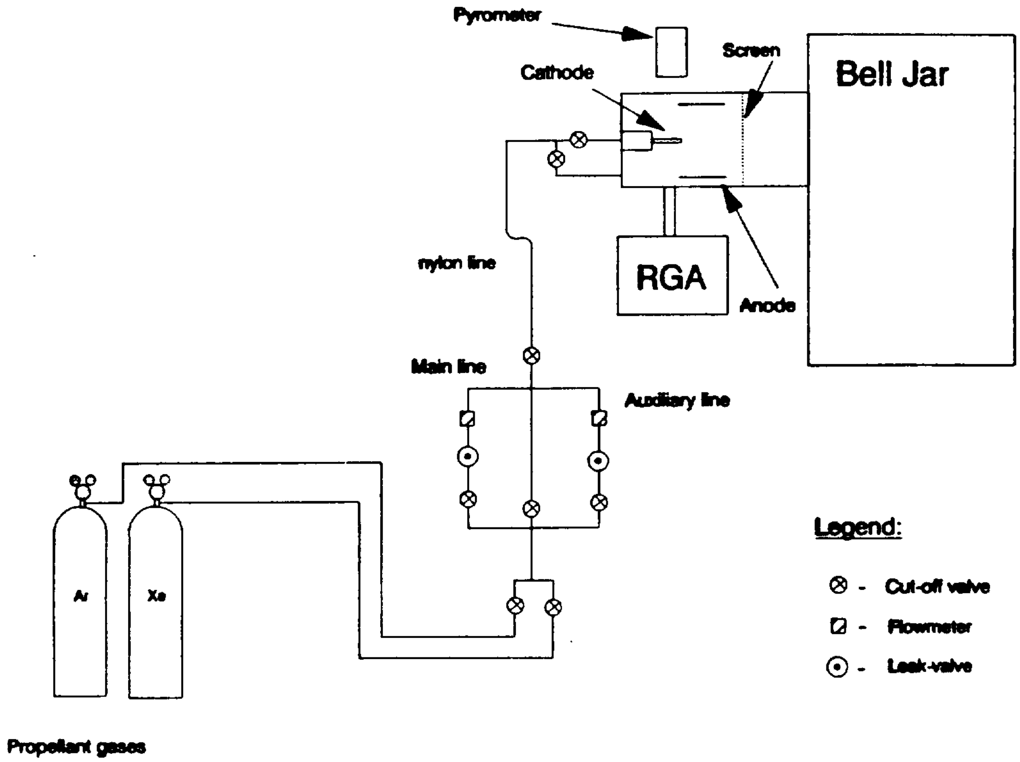


Figure 2. Schematic of the Hollow Cathode Test Facility.

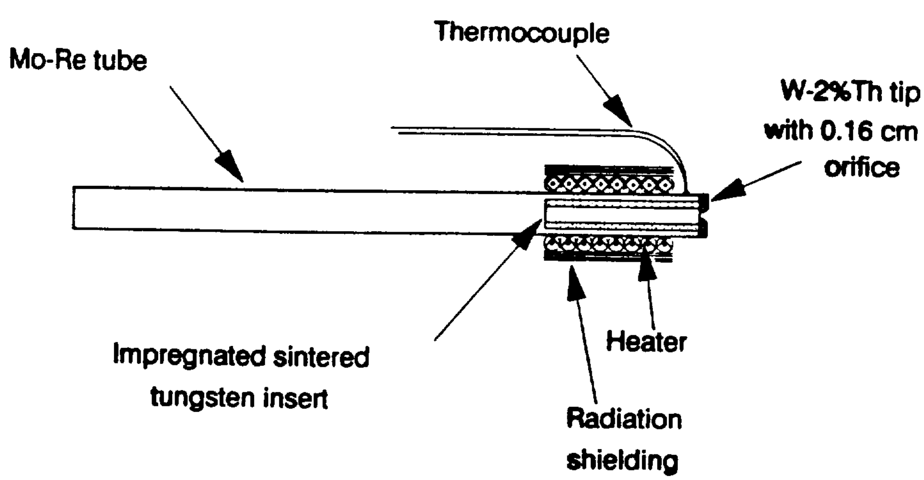


Figure 3. Schematic of the Hollow Cathode.

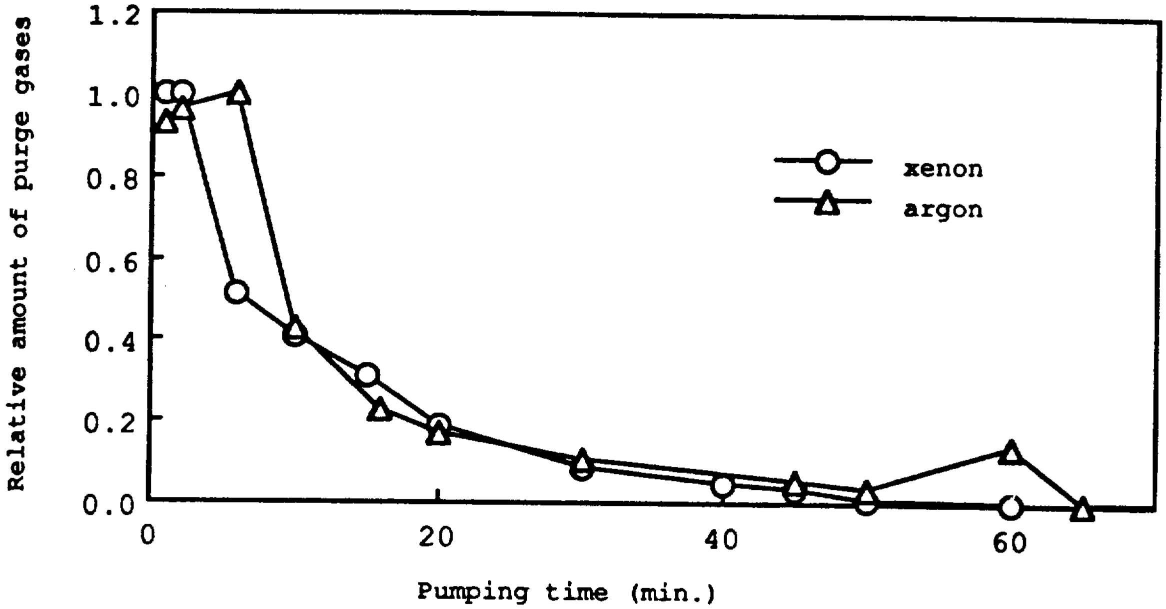


Figure 4. Pumping time of the inert gases. The gas levels are given with respect to the initial level of the inert gas at the beginning of the system evacuation. In both cases, the gases were flowed at 32 sccm prior to test.

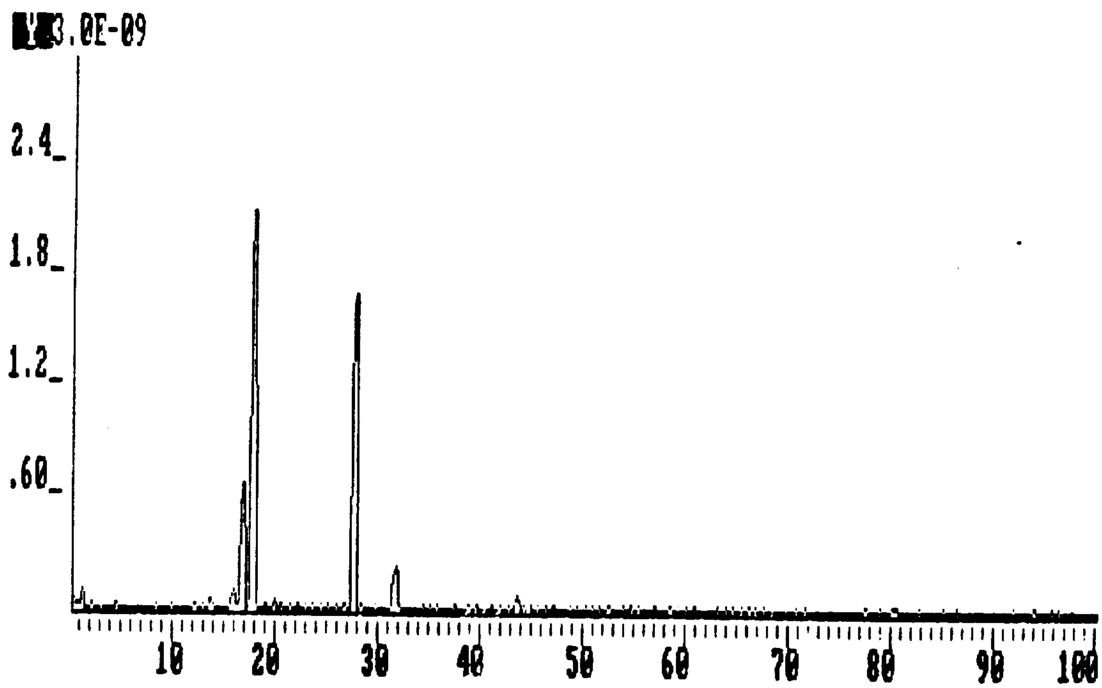


Figure 5. Residual gas analyzer scan of the atmosphere within the simulator chamber and propellant feed-system. All values of partial pressures are relative to the total pressure measurement by the RGA and require correction for absolute values.

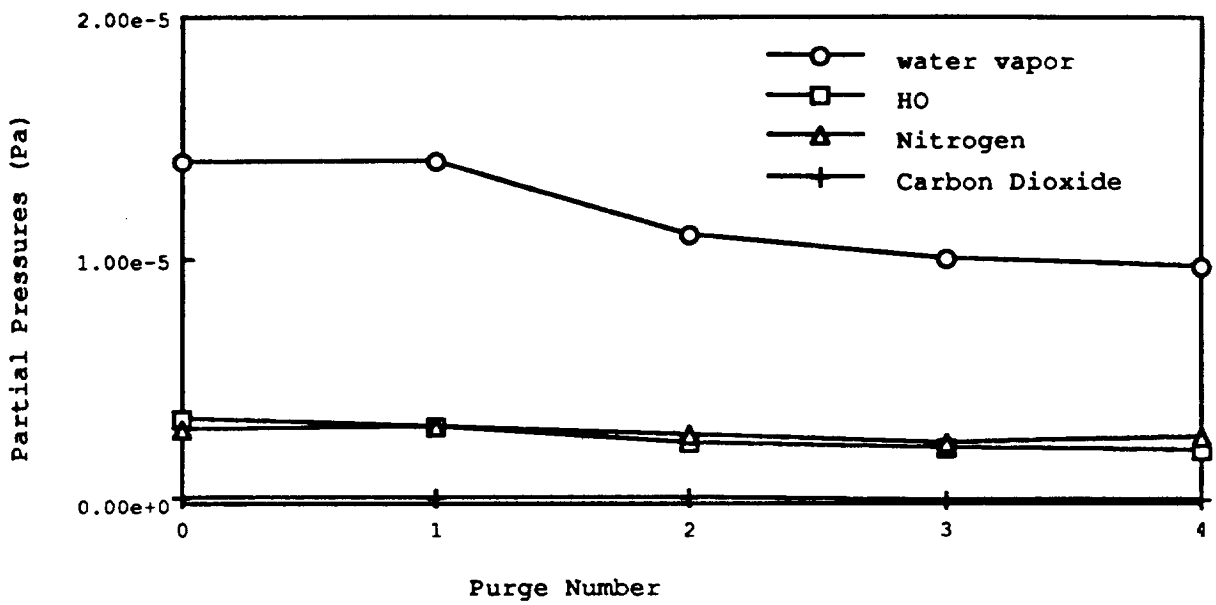


Figure 6. Relative partial pressures of various contaminants in the simulator chamber and propellant feed-system with respect to the number of repeated argon gas purges of the feedlines. The purge consisted of flowing argon at 32 sccm for 10 minutes.

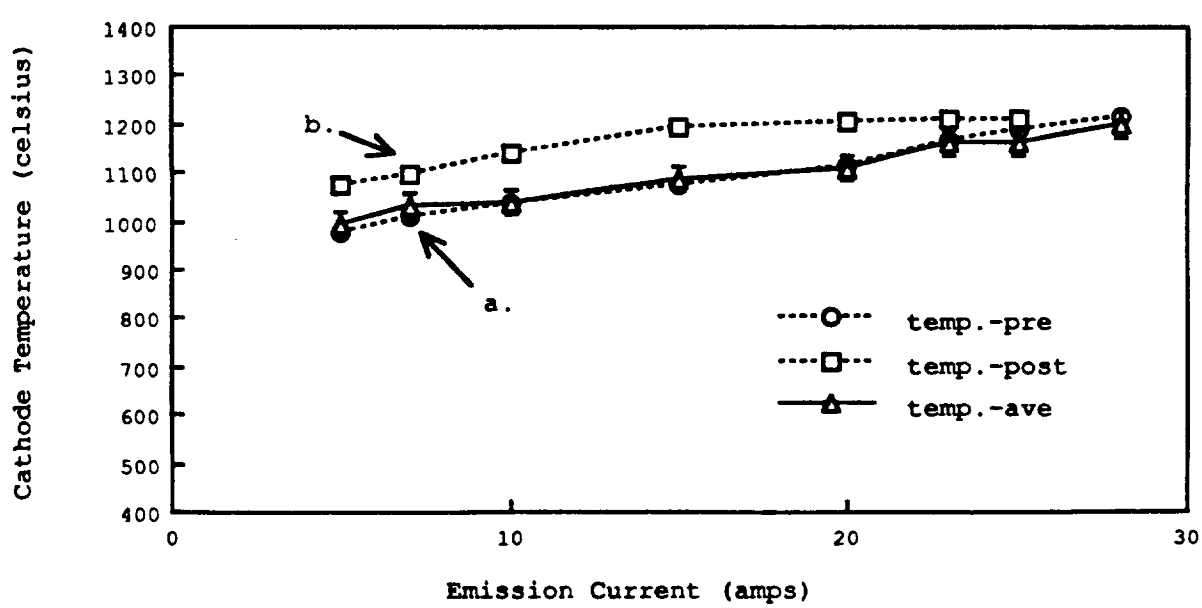


Figure 7. Temperature of the cathode body tube versus the emission current of the cathode. The cathode was operated with 6.1 sccm of xenon flow. The other curves represent measurements taken prior to (curve a) and after the 500-hour wear test (curve b).

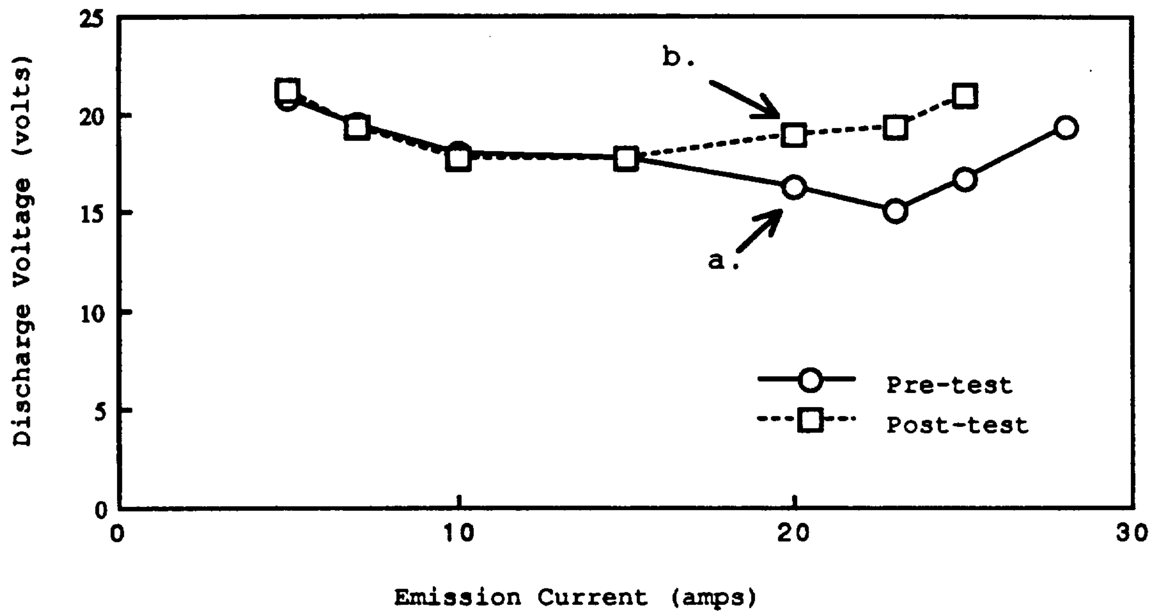


Figure 8. The discharge voltage of the hollow cathode versus the emission current. The cathode was operated with 6.1 sccm of xenon flow. Curves a. and b. represent the values taken prior to and after the weartest, respectively.

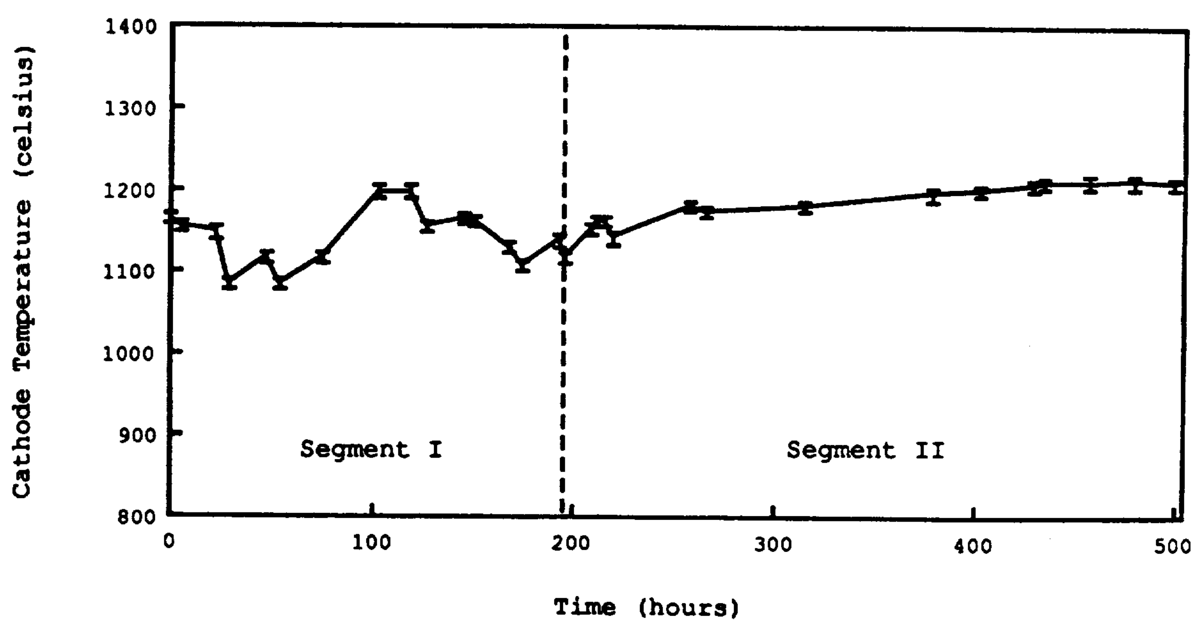
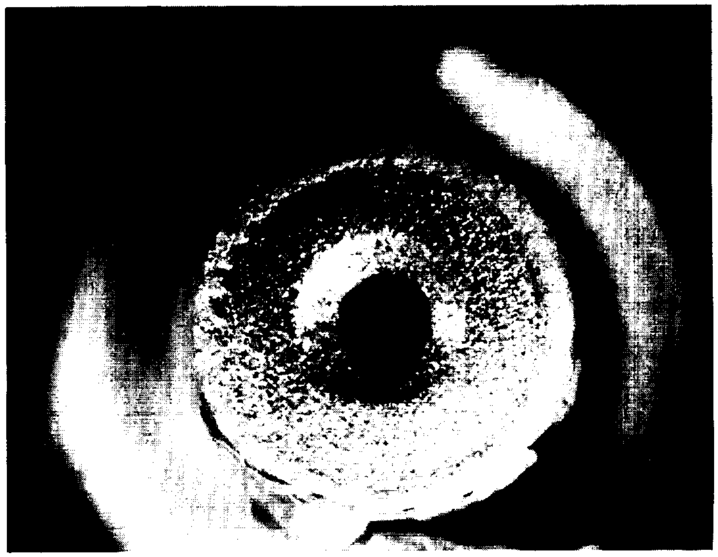


Figure 9. Temperature of the cathode body tube for the duration of the wear test. The cathode was operated at 23.0 emission current, an average of 18 volts discharge voltage, and 6.1 sccm of xenon flow.

a.



b.

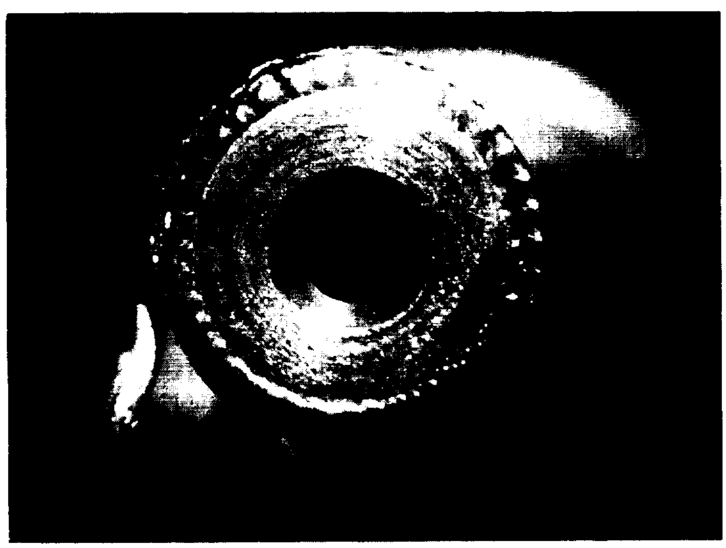


Figure 10. Condition of the hollow cathode orifce plate. Photo a. is of a cathode orifice plate with no operational time. Photo b. is the orfice plate after the 500 hour weartest.

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16. Abstract

An experimental investigation was initiated to establish conditioning procedures for reliable hollow cathode operation via the characterization of critical parameters in a representative cathode test facility. From vacuum pumpdown rates, it was found that approximately 1.5 hours were required to achieve pressure levels within 5 percent of the lowest attainable pressure for this facility, depending on the purge conditions. The facility atmosphere was determined by a residual gas analyzer to be composed of primarily air and water vapor. The effects of vacuum pumping and inert gas purging were evaluated. A maximum effective leakage rate of 2.0×10^{-3} sccm was observed and its probable causes were examined. An extended test of a 0.64 cm diameter Mo-Re hollow cathode was successfully completed. This test ran for 504 hours at an emission current of 23.0 amperes and a xenon flow rate of 6.1 sccm. Discharge voltage rose continuously from 15 to 21 volts over the course of the test. The temperature of the cathode body during the test was relatively stable at 1160 °C. Post-test examination revealed ion-bombardment texturing of the orifice plate to be the only detectable sign of wear on the hollow cathode.

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